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Eco-Informatics for Decision Makers: *Advancing a Research Agenda*

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Report of an NSF- and USGS/NBII-sponsored Workshop on *Eco-Informatics for Resource Management Decision Makers* held at The Evergreen State College, Olympia, Washington, December 13-15, 2004, and organized by EPA, NASA, NSF, USDA Forest Service, and USGS/NBII.

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Executive Summary

Eco-informatics (sometimes referred to as ecosystem informatics) is the management and analysis of ecological information and the facilitation of large-scale ecological research through the application of computer technology.[2] In June 2000, the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), and the U.S. Geological Survey (USGS)-National Biological Information Infrastructure (NBII) held the first workshop on Biodiversity and Ecosystem Informatics (BDEI). At this workshop, scientists and natural resource managers examined the prospects for advancing computer science and information technology by focusing on the needs of the biodiversity and ecosystem domain, detailing issues raised earlier in the 1998 President's Committee of Advisors on Science and Technology (PCAST) report, "Teaming with Life: Investing in Science to Understand and Use America's Living Capital." The tools needed to solve ecological problems and other environmental challenges are currently being researched and developed under the rubric of eco-informatics.

Most eco-informatics research efforts since the PCAST report and the June 2000 workshop have focused on improving productivity in research and increasing the availability of published research data to other researchers. In mid-2004, participants at an NSF Digital Government conference explicitly extended the eco-informatics vision to include decision makers (e.g., policy makers and natural resource managers) who need better eco-informatics products, and recommended that NSF and USGS convene a workshop devoted to the needs of decision makers regarding eco-informatics. As a result, NSF and USGS charged that this workshop, held in December 2004, focus specifically on informatics tools to support ecological and environmental decision makers.

To solve the eco-informatics problems faced by natural resource decision makers, it is necessary to sustain and encourage innovation, research, and development in the public and non-governmental sectors. To map this problem space, the considerable experience of various organizations who develop information technology for natural resource decision makers should be noted. At the December 2004 workshop, participants from these organizations articulated the context of the eco-informatics problem space. Eco-informatics, they said, is about (1) both biodiversity-rich, conservation-managed systems and natural resource protection; and (2) the impacts of environmental, anthropogenic pollutants. Researchers in this area must consider

[1]This workshop was supported by the National Science Foundation Digital Government Program under grant NSF IIS 0505790, and the U.S. Geological Survey. All opinions, findings, conclusions, and recommendations in any material resulting from this workshop are those of the workshop participants and do not necessarily reflect the view of the sponsoring agencies.
See the workshop web site at <http://www.evergreen.edu/bdei>.
[2]See <http://www.ecoinformatics.org>.

combining quantitative with qualitative information, and have a basic understanding of decision making.

Collaborative data exchanges between the U.S. Environmental Protection Agency (EPA) and the Environmental Council of the States (ECOS), as well as NSF- and USGS-funded university research projects highlighting how geospatial information aids government agencies charged with developing coastal policy, have successfully demonstrated how current and future eco-informatics efforts might engender better resource management. Drawing on these and other successes, participants at the December 2004 workshop concluded that the problem space for natural resource management and eco-informatics comprises the following areas: policy, data presentation, data gaps, tools, and indicators.

To develop research issues from the above natural resource management problem space, workshop participants approached the problems in an interdisciplinary manner, articulated research issues, critiqued those issues, and prioritized strategies for sustaining research. Case studies from the May 2004 NSF Digital Government conference were used as models for identifying research issues, which were categorized into one of four major areas: modeling and simulation, data quality, data integration and ontologies, and social and human aspects.

Participants warned that without significant and sustained research into eco-informatics tools in the above areas to more effectively and efficiently manage our natural resources, the country will not keep pace with increasing natural resources demand. Further, research results alone are not enough; research must be refined and research prototypes developed in collaboration with resource managers. Research prototypes must be migrated into software products and then tested by resource managers and refined accordingly—again through collaboration between the academy and those charged with managing our nation's resources.

Finally, software and other informatics products must be readily available to agencies and nongovernmental organizations (NGOs), organizational processes for technology adoption should be put in place, and the effectiveness of technology use should be determined. "Round-trip" engineering best practices and software clearinghouses, so successful in industry, must be adapted and applied to this domain. In other words, new funds and new practices for long-term collaborations among research and government organizations, and NGOs that manage natural resources, must be initiated. Traditional three-year research grants are only a start toward solving these issues.

The sheer number, breadth, and complexity of the problems and potential solutions suggested at the December 2004 workshop dictate that it will take decades to solve the problems, which may be too late to save deteriorating ecosystems and disappearing species. Participants in the workshop therefore determined that the research community and decision makers need to work together to continually prioritize the critical problems and identify where those problems intersect across agencies and environments to create the greatest synergies with limited funds. Understanding the nature of decision making while ascertaining feedback will be critical to those conducting research in eco-informatics. Thus, in addition to understanding major research themes, those conducting research in this area should understand fundamental concepts of decision making in general, and how those concepts play out in the context of eco-informatics.

Another future challenge is to train computer scientists, social scientists, and biologists, among others, to work in eco-informatics and natural resource management. Funding agencies such as NSF and other government agencies must work together and with principal investigators, information managers, and decision makers to sustain and encourage innovation, research, and development in this area. Attention should be paid to assuring a cycle of innovation from research to prototype, to development and commercialization, to deployment and evaluation. In addition, funding and reward systems within both the academy and agencies must be adjusted to facilitate such a cycle. Also, attention must be paid to reprioritizing the research agenda as needed to assure the development of tools that can be applied to a wide range of ecological and environmental problems. Finally, workshop participants felt that a cross-agency funding initiative should be pursued to support the major research challenges outlined in this report.

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Abstract. Resource managers often face significant information technology (IT) problems when integrating ecological or environmental information to make decisions. At a workshop sponsored by the National Science Foundation (NSF) and the U.S. Geological Survey (USGS) in December 2004, university researchers, natural resource managers, and information managers met to articulate IT problems facing ecology and environmental decision makers. Decision-making IT problems were identified in five areas: (1) policy, (2) data presentation, (3) data gaps, (4) tools, and (5) indicators. To alleviate those problems, workshop participants recommended specific informatics research in modeling and simulation, data quality, information integration and ontologies, and social and human aspects. This paper reports the workshop findings, and briefly compares these with research that traditionally falls under the emerging eco-informatics rubric.

Introduction[4]

In June 2000, at the first NSF-USGS-NASA workshop on Biodiversity and Ecosystem Informatics (BDEI), a group of computer scientists, biologists, and natural resource managers met at NASA Goddard Space Flight Center to examine the prospects for advancing computer science and information technology by focusing on the needs of the biodiversity and ecosystem domain. The following scenario, taken from that workshop report,[5] illustrates problems faced by natural resource managers and how information technology might alleviate those problems. Eco-informatics research funded in 2002 by the NSF as a result of that workshop's recommendations addressed only some of the problems raised in the scenario.[6] Because so many critical informatics problems remain for resource managers, the NSF, USGS, and NASA, together with the Environmental Protection Agency (EPA), convened a major workshop in December 2004 to address natural resource management. This document reports that workshop's findings, as introduced by Karen's story, which illus-

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[4]From BDEI 1 report, *Research Directions in Biodiversity and Ecosystem Informatics*.
[5]"Karen's Story" was developed by workshop report authors Dave Maier and Eric Landis to illustrate problems faced by a natural resource manager. It is used here with their permission. See <http://www.evergreen.edu/bdei/2001> for the full report of that workshop.
[6]For a report of that research, see <http://www.evergreen.edu/bdei/2003>.

trates crucial information technology problems still faced by resource managers.

It's Tuesday afternoon. Karen Culver has just been asked by her boss at the state fish and game agency to address a meeting of the Eagle River Watershed Council. The council is presenting a restoration plan for Silver Creek, with the particular goal of improving bull trout habitat. One aspect of the plan involves removing a small diversion channel that feeds an irrigation pond, with the expectation that this would improve stream flows and lower water temperatures in the summer. The proposal is to replace the irrigation water drawn from the creek using a pipeline or culvert from another nearby water source to the pond. Local landowners and members of the public have been at odds about whether closing the existing channel would have much benefit, and what the adverse effects and costs might be for installing a culvert or a pipeline.

Karen thinks she could compile the scientific information relating to these issues in about six weeks. To do this, she needs topographic maps of the Silver Creek drainage and surrounding area to identify possible sources for replacement irrigation water and likely routings of a culvert or pipeline. She also needs to locate any recent hydrology studies and fish counts of Silver Creek. Karen must also check what the ownership and land use is of areas that a culvert may cross. If she could retrieve the appropriate meteorological data, along with the topographic and hydrologic data, maybe her co-worker, Tom Hamilton, could run a simple model to project Silver Creek's stream flow, water temperature, and downstream sedimentation after closing the channel. With that information, she might be able to look for streams with similar characteristics and determine what bull trout populations they support. Then she would need to get those tables of numbers into a form understandable to everyone at the upcoming meeting. Maybe she can go through agency archives to see if there are any historical surveys of the area before the channel was dug in 1932. She also wonders whether there are any sensitive populations of other plant or animal species currently dwelling in the creek or channel. It would be helpful to go into the field and examine the Silver Creek area, but it's 220 miles away in the southwestern corner of the state. Besides, the watershed council meeting is Friday morning. Karen has three days, not six weeks.

Karen's situation typifies problems that arise in trying to answer management and scientific questions about species diversity and ecosystem health using the current information infrastructure available to resource managers. Relevant information is difficult to locate (if it exists at all), and may be in a variety of digital and nondigital forms. Integrating the information and putting it into a form suitable for use with a specific analytic tool usually involves intensive and time-consuming human interactions with the data. Visualizations of data sets are not easy to construct quickly. And the questions are posed in a climate of increasing public scrutiny of agency decisions and concern about species and ecosystem preservation.

It's 2010, and Karen Culver is once again evaluating the proposed closure of the Silver Creek diversion channel. Back in 2001, the channel wasn't closed. While she had felt that closing the diversion channel would have helped the bull trout population, in the limited time available, she wasn't able to get all the information she needed to make an effective presentation to the local council.

The channel is now in need of repair, and closure is being considered again. To get a feel for the situation, Karen is at the site where the channel leaves the stream. She dons a pair of visualization goggles that interface with her portable computer. Using voice commands, Karen can overlay her view of the terrain with different maps and data sets. She quickly superimposes land ownership, topographic lines, and locations of previous biological studies. She is also able to view the creek in false color to see seasonal temperature variations and flow rates. She focuses her gaze on the channel and brings up counts of species that have been surveyed there. She *notes that there has been an observation of a species of tiger salamander listed as threatened.*

She switches to the screen of her portable computer to look at the area in plane view. She examines some aerial imagery of the drainage and adds a map showing the location of the farms that draw water from the irrigation pond the channel supplies, plus another map showing land ownership and use in the area. Using this information, she starts sketching a route to nearby Crabb Lake, which could supply replacement water.

Karen now turns to the effects of channel closure. She gets her co-worker, Tom Hamilton, online and he helps her select a model to use for predictions. He shows her how to work a wizard that can help select and convert appropriate data sets for use with the model. Within about fifteen minutes Tom and Karen have located suitable topographic and meteorological data, and the wizard has suggested two possible hydrologic data sets. Tom recommends using the second one, as it has more complete historical coverage. The model is then dispatched to run remotely on a computer server, to work through the range of expected stream temperatures and flows if the channel were closed. Although Karen isn't explicitly aware of it, the computation is actually split into three parts, which take place on three different high-performance cluster computers.

Karen is also wondering about the sedimentation of downstream gravel beds where bull trout currently lay eggs. She does a similarity search for documents about other stream modifications in areas with comparable soil types and hydrology. She finds six and examines them to find which most closely match the current situation.

The model calculations on predicted temperatures and flows after closing the channel are done and have been transferred to Karen's portable, as well as sent to Tom back at the main office. She gets him back online to help interpret them in terms of effect on fish. He helps her construct a plot comparing the periods each year when water temperature or oxygen levels are likely to adversely affect the fish. They compare that plot to one based on records from a recent year. They see that the closure would likely yield a great improvement, with periods of adverse conditions being both shorter and less frequent. With a little help from Tom, she launches a task to render an animation of water conditions before and after closure, with a color spectrum representing favorable to adverse conditions. That task is routed to a remote server; all Karen cares about is that an MPEG-9 file for the animation is downloaded onto her portable when she gives her presentation to the watershed council that afternoon.

The one remaining issue for Karen is still the tiger salamanders in the creek. She'd really like to know if that species of salamander was present before the channel was dug (and thus can be expected to survive if the creek returns to a similar state). Unfortunately, amphibian survey data on Silver Creek only go back about 15 years. Karen has an idea, however. She dispatches a query through the National Biological Information Infrastructure to search holdings of natural history collections throughout the country. In about four minutes, she gets back two records of tiger salamanders collected at Silver Creek, in 1914 and 1933. She is quite impressed by the results, as the query system knew that Silver Creek was called Sinners Creek before 1920, and that the scientific name of that particular species had been modified in the 1950s. She is able to view the digitized label information for the 1933 specimen, which contains an annotation that tiger salamanders were abundant at several places in the stream, including one site near the channel junction. She is reassured that there likely will be suitable habitat for the salamanders if the channel is closed, though there will still need to be some further study.

Karen sets off to her afternoon council meeting feeling much more confident about the presentation she's going to make than she did nine years earlier. She did in *three hours what she was unable to do in three days in 2001.*

This is how we hoped Karen's story would "end" in 2010—if the research agenda set forth by participants of the first workshop were accomplished and if it were integrated into information technology products readily available to resource managers. Unfortunately for resource managers, limited funds were made available in 2001 for eco-informatics research and 13 planning grants from NSF that year made progress in only some of the areas where Karen needs help (see preliminary reports from these 13 planning grants at <http://www.evergreen.edu/bdei/2003>):

- Flyover data views
- Data tagged with processes and events
- Hydrology data for sedimentation
- Species information related to place
- Taxonomic browsing adjusted to change
- Summary habitat and adverse habitability periods
- Digital metadata
- Public survey data
- Help in finding and running models

Most of the above research (as well as much other current eco-informatics research) is aimed primarily at tools to help ecology researchers, not resource data managers. The reasons for this are understandable: it is easier for computer science researchers who work in universities to collaborate with other researchers than with resource managers. Moreover, it is well known that informatics problems related to public policy are complex and difficult to understand and solve. Thus, the following explicit research needs illustrated by Karen's story still remain:

- Visualizations for public education
- Field-to-office collaboration
- What-if scenario modeling
- Place-name semantics (geo-location, changes)
- Similarity search on documents
- Natural history collection access
- Augmented reality glasses
- Derived data product definitions

We thus observe that five problem areas will continue to plague resource managers unless further research dollars are devoted to this domain: policy, data presentation, data gaps, tools, and indicators. Further, we cannot assume that eco-informatics research, even if successful, will make its way to the desktop and fieldwork of resource managers. Technology transfer, from research prototype to finished product, is a difficult task. Participants in the 2004 workshop identified four critical research areas where considerable work is required to solve problems in the above areas:

1. **Social and Human Aspects.** We need to foster collaboration in tool development and information sharing; to advance human-computer interaction (HCI); to develop management practices, education, and training in data management; and to develop user requirements.

2. **Data Quality.** We need to determine and figure the impact on decision making of uncertainty with multiple data sources, associating error and metadata.

3. **Information Integration and Ontologies.** We need *multiple* ontologies and document modeling; tools for integrating qualitative and quantitative data at both the syntactic and semantic levels; and methods for evaluating knowledge from nontraditional sources.

4. **Modeling.** We need experience and tools for coupling, visualization, and uncertainty, as well as a national infrastructure for developing and using models.

Background: Eco-Informatics

The informatics tools needed to solve environmental challenges (e.g., global climate change, emerging diseases, decreasing biodiversity, and waning resources) are currently being researched and developed under the rubric of eco-informatics. These needs were articulated in the 1998 President's Committee of Advisors on Science and Technology (PCAST) report, "Teaming with Life: Investing in Science to Understand and Use America's Living Capital," which characterized bioinformatics as a biology and computer science/information technology (CS/IT) cross-discipline, recognized the biodiversity-ecosystem nexus as an information enterprise, and envisioned analytical and synthetic capabilities among other foci in the next generation of the National Biological Information Infrastructure (NBII)-2 information services.[7]

Most eco-informatics research efforts subsequent to PCAST, and as articulated by researchers and agency representatives at workshops[8] sponsored by the NSF, NASA, and the NBII, have focused on tools to help improve research productivity and increase the published availability of research data. A growing body of research has emanated from these and similar efforts.

In mid-2004, researchers at an NSF Digital Government Conference participated in a lively conversation on the future directions of eco-informatics.[9] They extended the eco-informatics vision to include the needs of decision makers (e.g., policy makers and natural resource managers) in utilizing eco-informatics products more effectively. They recommended that the NSF and the USGS fund a workshop devoted to decision-maker needs regarding eco-informatics. Thus, the December 2004 workshop focused specifically on informatics tools to support ecological and environmental decision makers.

Information technology is critical to natural resource managers. At this point, however, the potential is far from being attained. Potential decision makers at all levels of government and at nongovernmental organizations (NGOs) that manage natural resources or carry out ecological or environmental policy often face significant information technology problems when integrating ecological or environmental information. Decision makers work with information providers and data managers, and seek a wide variety of information sources, but little of the data provided by these sources is collected specifically for the decision making at hand. Thus the decision maker is faced (often indirectly) with many information technology issues, including data gaps, data presentation, and how to use or create appropriate indicators. These issues point to computer science research needs in information integration, modeling and simulation, data quality, and human-centered areas, such as training, technology transfer, best practices for information provision and use, and human-friendly software.

Eco-informatics problems faced by natural resource decision makers require, in addition to new research, particular efforts to sustain and encourage innovation, research, and development in the public and NGO sectors. These findings are not unlike needs articulated by digital

[7]The PCAST report is available at <http://www.nbii.gov/about/pubs/twl.pdf>.
[8]See <www.evergreen.edu/bdei>.
[9]See the National Conference on Digital Government Research web site at <http://www.dgrc.org/dgo2004>. The Eco-Informatics Birds of a Feather (BoF) participants were Chaitan Baru, Judith Cushing, Stefan Falke, Mike Frame, Bill Hodgkiss, Eric Landis, Maria Matevosyan, Peter McCartney, G. P. Patil, Jon Schweiss, Sharon Shin, William Sonntag, Sylvia Spengler, Charles Taillie, Bill Waltman, Jessie Wilbur, and Tyrone Wilson. Special thanks to Val Gregg (NSF), Sue Stendebach (EPA), and Bruce Bargmeyer (LLBL), who helped to formulate the agenda.

government researchers.[10] Eduard Hovy, calling on his experience with eco-informatics projects funded by the NSF Digital Government program, notes that considerable attention must be paid to finding the right domain problem to focus on, distilling a range of research that will prove fruitful to multiple stakeholders, finding the right agency collaborators, and then managing expectations.[11]

Researchers in this area must consider combining quantitative with qualitative information, and have a basic understanding of decision making. Like other scientific computing research, the field would benefit greatly from considerable open-source, flexible infrastructure (such as a reusable modeling infrastructure), along with the social practices that would sustain it. If computer scientists and social scientists in the academy are not prepared to take on these challenges, in addition to demanding research, workshop participants believe that natural resource eco-informatics will continue to lag considerably behind informatics in other science and policy domains. This prediction is based on the complexity introduced by public policy requirements added to already complex scientific informatics issues. Solving these problems is not simply a matter of adopting technology developed for another domain.

[10]Examples include those articulated at a May 2005 panel at the National Conference for Digital Government Research organized by Lois Delcambre and Gen Guiliano; see <http://dgrc.org/dgo2005>.
[11]See <http://www.evergreen.edu/bdei/presentations/hovy.pdf>.

Eco-Informatics and Natural Resource Management: Five Problem Areas

Eco-informatics is about both biodiversity-rich, conservation-managed systems and natural resource protection, on the one hand, and the impacts of environmental, anthropogenic pollutants on the other. Rather than sorting out different informatics needs for these two separate areas, the workshop recognized that the latter area likely presupposes a command of the former, and they thus focused primarily on non-human-health-centered ecological constituencies. Another perspective can be found in Europe, where the research is much broader in nature and includes health and security, as well as ecosystem function.[12]

To map the problem space for natural resource management eco-informatics, we note that many organizations now have considerable experience developing information technology for natural resource decision makers. At the workshop, the context of what we call the eco-informatics problem space was laid out by representatives from the USGS, the EPA, the USDA Forest Service, NASA, state agencies, and Interstate Consortia, such as the State/EPA Environmental Information Exchange Network. Policy makers and their clients' information needs form communities of interest, as well as place, and thus the required information technology is very broad. An example of a community of place is the ecology of Mount Rainier, which is a well-loved, locally used park in the Pacific Northwest. One can easily see, however, both communities of place and interest with regard to the Escalante Natural Monument, which might be valued locally for grazing, but nationally for its special scenery. The possible political aspects of certain data make equitable information access and mass customization necessary, as well as the need to clearly distinguish between measurements, indicators, and interpretations. Finally, metadata and validation are all essential to biodiversity and ecosystem decision making. As Rich Guldin stated in his presentation: "Better data lead to better dialogue, which leads to better decisions."

As Larry Sugarbaker of NatureServe observed, people working on projects at nongovernmental agencies have found that conservation informatics is hard and that data and tools form a demand cycle: the more successful tools are, the more demand arises. Biodiversity data management and collection would be more efficient if data were managed in common formats, with better decision-support tools, such as a common framework for geographic information. As we know from other scientific application areas, however, requirements for common frameworks come with their own sets of problems.

In spite of these contextual challenges, some successful exemplary projects demonstrate how current and future eco-informatics might be used to engender better resource management. A recently deployed collaborative project between the EPA and the Environmental Council of the States (ECOS) improves secure data exchange and timeliness between states and the EPA via web services and facilitates the adoption of new standards. Fish tissue contamination and birth defects assessment has been a key first application of this technology. As evidence of the perceived value of this collaboration, many states, surprisingly, have been ready with data even earlier than the jointly agreed-upon deadline. NASA's Science Mission experience with decision support for earth science, particularly for the invasive species project, shows how remotely sensed raw data (observations) can now be used in conjunction with models (predictions) as input to decision support tools.

Two NSF projects, one at Ohio State University and the other at Oregon State

[12]See <https:// www.evergreen.edu/bdei/presentations/jensen.pdf>.

University, demonstrate successful collaboration between university researchers and coastal policy makers and exemplify the complexity of informatics problems. The coastal zone is an interaction zone of land, sea, and air. Although the coastal zone occupies only 3 percent of all the sea surface area and 0.5 percent of ocean volume, about 70 percent of global fish resources spend part of their life in the coastal area. About 60 percent of the world's human population resides close to the coastal zone, which is exploited by humans for food, recreation, transport, waste disposal, and other needs. With the increase of human activities, many materials discharged from the land spread to the coastal area and cause environmental changes through various physical, chemical, and biological processes.

Excessive discharge and uncontrolled human activities in the coastal zone create environmental problems, such as habitat modification and destruction and ocean pollution. For instance, excessive loading of nutrients from watershed and various dredging operations and shoreline development may result in a loss of seagrass beds. Research indicates that the factors controlling seagrass distribution include nutrient loading, water quality, light, water depth, tide and water movement, salinity, temperature, climate change, and anthropogenic impacts. To facilitate sustainable coastal management, an important focus is to investigate the natural variability of coastal ecosystems and the complex interactions between biological and physical systems in coastal environments. Research integrating remote-sensing techniques and three-dimensional conceptual and quantitative models is needed to explore physical, chemical, and biological processes in coastal environments.

To integrate this multisource biochemical and geospatial information, both enhanced data-handling capacity and cooperation among intergovernmental agencies are essential. In Oregon and Tampa Bay, community partnerships have yielded some success in the areas of hazards management, watershed assessment, and ocean protection, where decisions depend on accurate resource status information; but they have been even more successful at highlighting the research needs required to monitor coastal eco-environmental changes and predict future impacts and possible hazards. More information about these case studies can be found on the workshop web site.[13]

Drawing on these and other successes, workshop participants categorized the problem space for natural resource management eco-informatics as falling into the following areas: policy, data presentation, data gaps, tools, and indicators.[14]

Policy

Areas to consider as part of the policy problem space related to ecological and environmental information and decision making include (but are not limited to) problems that organizations (across all sectors—public, private, and nonprofit) encounter because of their policies related to (1) the provision, production, and maintenance of eco-informatics tools and information; (2) the use (and possible abuse) of eco-informatics tools and information; (3) the cross-organizational sharing (or lack thereof) of eco-informatics tools and information; and (4) the communication (or lack thereof) of environmental management decisions grounded on eco-informatics-based analysis. The specific details of each problem area are as follows:

1. **The provision (e.g., financing), production, and maintenance (e.g., data curation or archiving) of eco-informatics (EI) tools and information.** Developers of EI tools and information need to begin with an understanding of user needs, but in some cases they are not doing so. Short-term research into why this is, how the problem differs

[13]See <http://www.evergreen.edu/bdei>.
[14]For the workshop presentations of the five discussion groups, see <https://www.evergreen.edu/bdei/presentations/ tuesbreakout1_combined.pdf>.

from other IT application areas, and how to solve the problem would be beneficial. It is relatively common, though costly and inefficient, that lots of data are collected but are used only once (or in some cases, not at all). Better systems of metadata and storage retrieval are needed to ensure that the data collected or generated are used (and shared) more frequently. In addition, organizations face a policy dilemma related to what kind of goods EI tools and information are: should they be treated as public, private, or toll goods? On the one hand, they could be considered public goods because they have the potential to be used by others outside the organization. On the other hand, there might be important reasons to treat them as a private or toll good in order to collect revenue to absorb some of the costs of producing this information.

2. **The use (and possible abuse) of eco-informatics tools and information.** How do you make the transition from uncertain scientific models to policy decisions requiring a legal burden of proof? How do you determine whether scientific evidence is adequate and defensible enough to justify a policy decision when there is uncertainty in that data? One participant noted that advances in this area include, for example, Bayesian statistical approaches. In some circumstances, EI tools that might be useful for policy analysis might not be used by decision makers (or more probably their advisors and analysts) because they (a) take too long (compared to the political cycle); (b) cost too much; (c) are based on too many unrealistic assumptions; or (d) are too complex or technical. This problem may be more salient at lower levels of government.

3. **The cross-organizational sharing (or lack thereof, e.g., privacy, confidentiality policies) of eco-informatics tools and information.** There are two levels of cooperation between organizations: the sharing of tools or EI information and the coproduction of tools or EI information. Collaboration might be more complex in coproduction situations than in sharing situations. Organizations tend to want to avoid paying to develop an eco-informatics tool or information if there is another organization also involved. One group member referred to this as a "tragedy of the commons" problem, and indeed, it is the classic free-rider problem in collective action theory. In addition, organization policies often act as barriers to the coproduction of eco-informatics tools or data sets. For example, if there is no recognition in an employee's performance review of effort expended to undertake and maintain cross-agency collaboration in EI tool or information production, that employee may be less interested in undertaking such endeavors again. In some instances, organizations might be interested in sharing information, but they may be hindered because inadequate metadata have been developed to communicate what the data sets represent. In the context of EI tools, such as models, there may be a similar interest in sharing, but there may be inadequate documentation (e.g., ontologies) that would promote model sharing and integration with other models. This problem is probably driven in part by a lack of attention in organizations to developing either a carrot or a stick approach for encouraging data owners to produce and maintain the metadata. Examples of carrot approaches are employee performance rewards or positive recognition in community of practice situations. Stick approaches include executive-order types of mandates with negative consequences to the employee if they are not followed.

4. **The communication (or lack thereof) of environmental management decisions grounded on eco-informatics-based analysis.** Organizations sometimes do a poor job of communicating pressing issues discovered through EI analysis to decision makers or the public. This is in part an information diffusion problem regarding the use of the media and other mass communication approaches. Organizations or policy makers are sometimes caught off guard by an

environmental or ecological problem and may find themselves facing real difficulties addressing it because little or no data exist to help understand and respond to it. Or there may be some data available, but the data exhibit a linear trend, when in fact the pattern is more complex. A question here is whether there are any EI-related tools and techniques that can help with this kind of situation. These are problems where decisions or policy need to be made under circumstances involving great uncertainty.[15]

Data Presentation

Data presentation problems arise from complex interactions between user needs (the nature of the required task and the time involved) and data (i.e., metadata, raw data, accuracy specifications, methods, documentation, policy). System limitations (e.g., software modalities, availability and costs of hardware) and information format further complicate presentation. Critical research includes determining what information is best on which medium, cross-referencing and supporting data across presentations, representing time and change, new media (e.g., 3D, virtual reality), and user task definitions. This problem area can be distilled into two major components. One is a model of the role of presentation as the "mediator" between users and their needs and the task and data/metadata and their characteristics. The second is the set of research questions and themes that relate to the facilitation of that mediation role.

Essentially, the model suggests that presentation options must reflect dimensions of the user experience, as well as the nature of the data, but also have their own sets of "constraints" or dimensions that need to be recognized in presentation. On the user side, presentation types may need to reflect a number of user dimensions: (1) user needs, perhaps conceptualized as tasks, or as time available to the user or his or her context for the activities; and (2) user characteristics, including preferences, disabilities, and computing capabilities. On the data side, presentation may need to reflect or take advantage of the nature of the data, the amount of data, the metadata available, the quality measures associated with the data/metadata, the data preparation activities used, and policies (such as privacy and confidentiality aspects). Presentation instantiations and approaches need to reflect the marriage of the user and the data sides. In addition, presentation media add their own "affordances" and issues to the mix that must be recognized. Different software modalities may have different suitabilities for different data types, and different hardware media have different costs, availability, and permanence. These three components of the model will suggest a range of research questions that will help us understand presentation for EI decision making.[16]

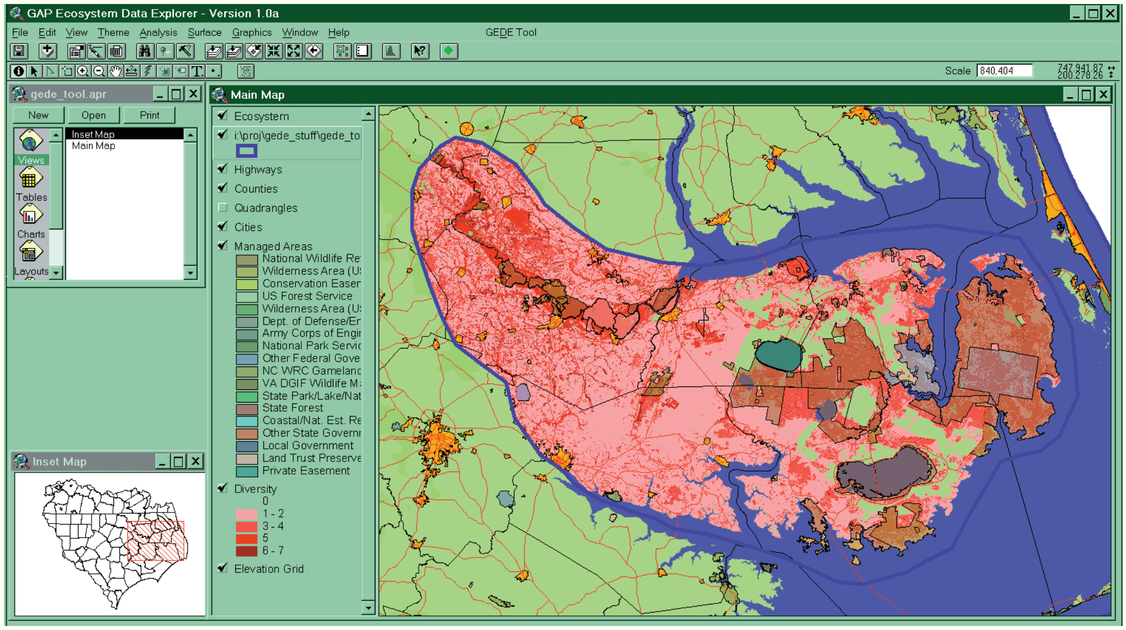
Data Gaps

Geographic data gaps between biodiversity-rich and conservation-managed land areas adversely impact decision making. These problems stem from a lack of needed data sets or access to them, disjointed data sets that require manipulation to compensate for temporal or spatial gaps, an emphasis on adaptive management that outpaces data reliability, and the lack of a network of database professionals who resource managers can call on for advice or expertise. Major issues include how to appropriately generalize fine-scale data, which will necessarily contain gaps, and the sensitivity of decision makers and policy makers to uncertainty. To refine this problem area, the next steps would address the original data needs and define review criteria, such as stable standards for data collection and documentation.

[15]For a more extensive treatment of this group's work, see <https://www.evergreen.edu/bdei/presentations/summaryPolicygroupfinal.pdf>.

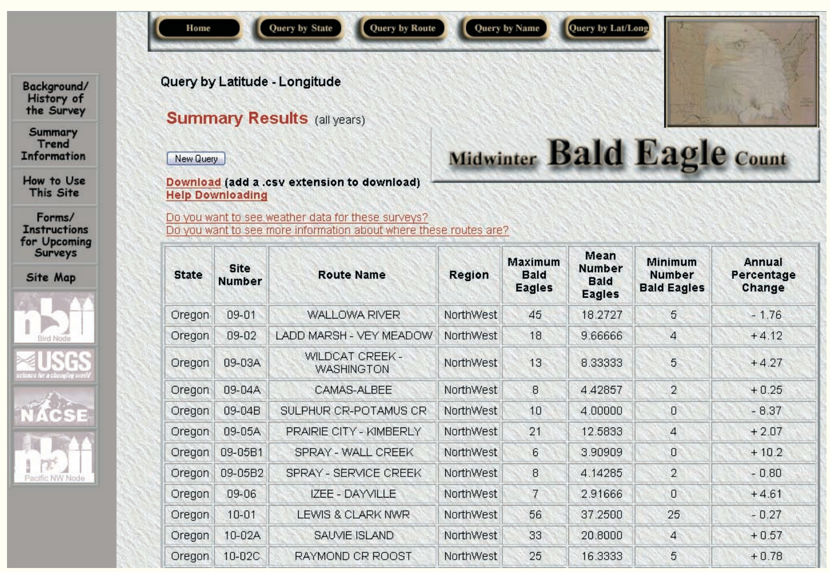
[16]For more details about data presentation, see <https://www.evergreen.edu/bdei/presentations/wedbo3summary.pdf>.

Identifying Co-incident Priorities for Bird Habitat and Carbon Sequestration

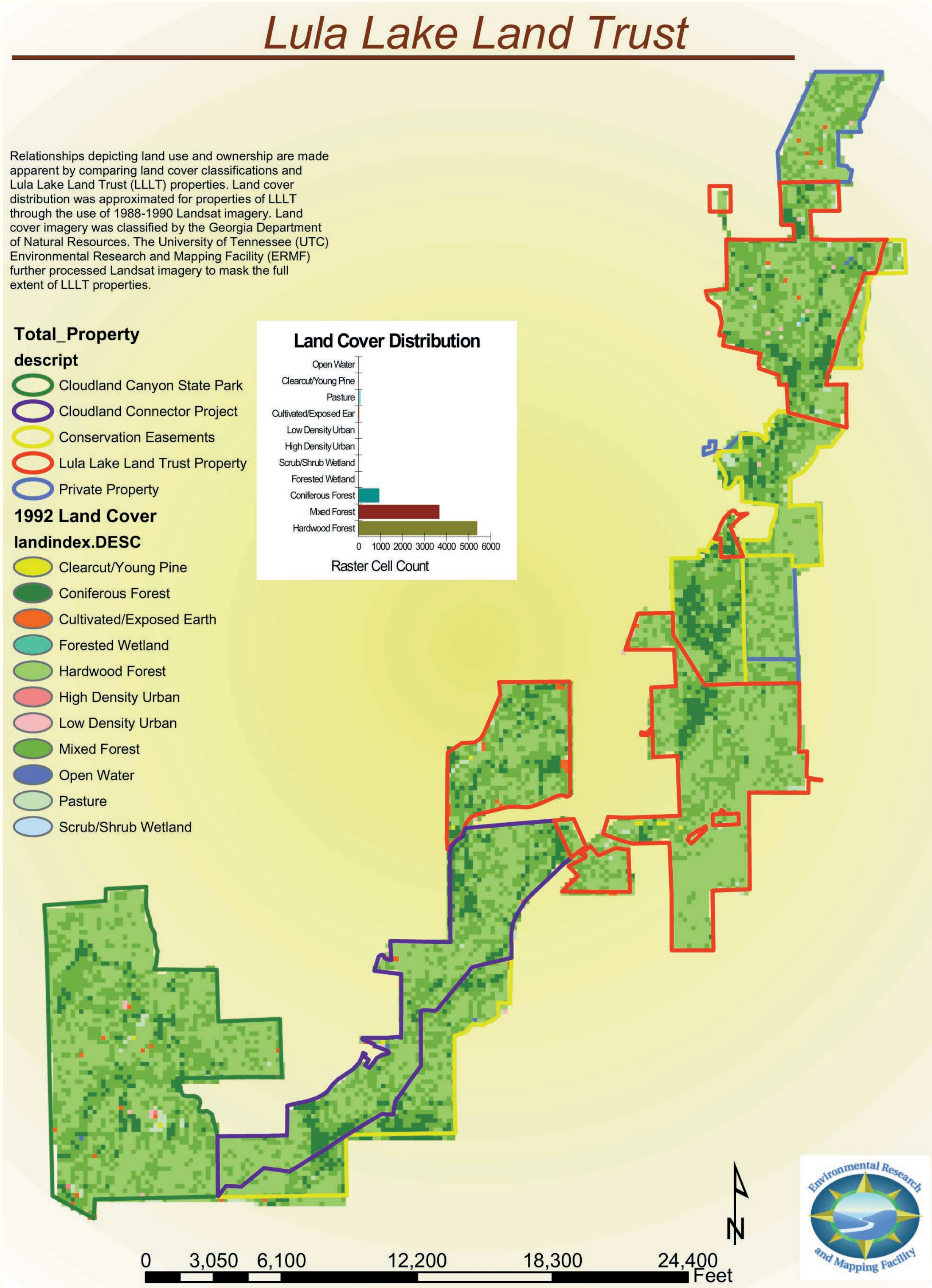


U.S. Fish and Wildlife Service (FWS) biologists have used the GAP Ecosystem Data Explorer (GEDE) decision support tool to identify areas on the ground where ecosystem restoration work could effectively identify (1) neotropical bird conservation and (2) carbon sequestration. The GEDE is a customized ArcView (ver. 3.2) project that displays and manipulates GAP data through a series of dialog boxes and avenue scripts. The GEDE tool allows non-GIS-savvy users to quickly view data and conduct advanced queries with a few simple clicks. Bob Noffsinger at the Habitat Management Office in Manteo, North Carolina, used GEDE to identify and analyze areas with organic soils suitable for reforestation. He refined the analysis by restricting the search to areas that, if restored, would build "interior" forest by adding to existing forested habitats, thereby benefiting several birds reliant on large tracts of intact forests. Not surprisingly, FWS has been able to use the tool for identifying conservation and habitat priorities, as well as identifying key data sets and functions. See <http://gcmd.nasa.gov/records/GEDET.html>.

Midwinter Bald Eagle Count Data Made Easier to Access



Through a collaboration between the NBII's Bird Conservation and Pacific Northwest nodes, managers of data resulting from the annual Midwinter Bald Eagle Survey no longer have to manually fill requests for information from this survey. Researchers, land managers, and others engaged in environmental studies who need information from the bald eagle survey can go directly to the Midwinter Bald Eagle Count web site coordinated by the USGS Forest and Rangeland Ecosystem Science Center's Snake River Field Station (SRFS). The database-driven web site allows for customizable queries on Midwinter Bald Eagle Survey results, as well as providing raw count data, summary information, and model-based estimates for trends from surveys along 563 routes in 42 states. It also provides an opportunity to monitor modifications or threats to habitat at important wintering areas. The survey has become a tradition that will likely continue in many states. In addition to providing information on eagle trends, distribution, and habitat, the survey has helped to create public interest in bald eagles and their conservation. See <http://ocid.nacse.org/qml/nbii/eagles/>.



Conservancy Outreach Project in the Southern Appalachians

The Conservancy Outreach project, a past project of the USGS Southern Appalachian Information Node in Chattanooga, Tennessee, developed a GIS-based conservation portfolio for several land conservancy organizations in the region. The conservation portfolios are analysis and assessment tools used by these organizations to help manage their conservation strategies. The portfolios were distributed on compact disks as stand-alone, self-executing GIS applications. The disks contained GIS support and customized geodatabase designs. Conservancy land managers are using these portfolios to determine sensitive habitats, to predict site suitability, and to schedule routine inventory activities based on the analysis of biotic and abiotic data sets. See <http://sain.nbii.org/databases_data.shtml>.

Tools

A major problem that was articulated applies across the board to scientific informatics research; namely, how one balances longer-term research to advance functionality with supporting users in the short term. Tool problems include the following:

- the lack of a tool "clearinghouse"; i.e., from the developer side, getting a tool out to users, and from the user side, finding and evaluating tools and determining whether a given tool can be applied to problems or input data that are different from what it was developed for
- the problems of new or different data types, and of data collection
- the lack of user frameworks and product suites, as well as development standards
- the lack of tools to support metadata issues (creation, quality, and so forth)
- the social science issues of usage, sharing, and adoption

The geographic information system (GIS)-based Conservancy Outreach project provides assessment tools for land conservancy managers (see example at left).

Indicators

Indicator problems exist because indicator definition, relevance, and value are neither well-defined, nor widely understood. Constituents may be uneasy with environmental measures, and data gaps affect reliability and the trust that these stakeholders have in indicators. Finally, the inherent complexity of the ecosystem complicates this issue. Prime examples of the complexity that arises in using indicators include the Death Valley Pupfish and the Washington State Shellfish Bed Closures.[17]

[17]See <https://www.evergreen.edu/bdei/presentations/wedbo3HumanCenterednesssummaryc.pdf>.

Eco-Informatics Research Required to Support Decision Makers: Four Foci

Teasing out the research issues from the natural resource management problem space was a four-step process:

1. Participants examined three current research projects to see how they employed interdisciplinary approaches and involved government partners to solve problems similar to those identified above.
2. Workshop participants broke into smaller groups to articulate research issues.
3. These research issues were critiqued by a panel of resource managers and researchers with experience in the area.
4. The smaller groups met to refine and prioritize the issues that had been articulated earlier to identify strategies for sustaining the research and to find resource management case histories that exemplified the need for the research they identified.[18]

The three NSF Digital Government research case studies were the Forest Portal, UrbanSim, and Understanding Government Statistics (GovStat):[19]

- The Forest Portal, an adaptive management tool that harvests information to sustain forests, highlighted the importance of collaboration between federal agencies and academic institutions, and demonstrated the capabilities of using metadata attachments.
- UrbanSim demonstrated how ecological models and establishing partnerships contribute to data collection, preparation, and assessment, which in turn likely led to realistic policy scenarios and major policy applications in 2005.
- The GovStat project models user access to U.S. government statistical information to better integrate data across agencies. In building a prototype to harvest government web pages, project designers emphasized the value of deployed prototypes to identify research challenges, in this case finding data that mapped to user requirements and designing an interface that relies on metadata generated from the web sites.

Research issues were categorized into one of four major areas: modeling and simulation, data quality, data integration and ontologies, and social and human aspects.

Modeling and Simulation

Modeling and simulation research issues emphasized by the group included coupling diverse models, addressing values in design (models for diverse stakeholders), incorporating new visualizations for model results, representing error and uncertainty when presenting information to decision makers, managing large data sets, and open-source modeling infrastructure. The group proposed an open-source, flexible, reusable modeling infrastructure, along with the social practices that would sustain it. This infrastructure would allow researchers and decision makers to experiment freely with new models and/or change existing ones.

Data Quality

The discussion of data quality research issues focused on how to determine uncertainty and communicate it to decision makers when using multiple data sources. Methods are needed to avoid introducing errors when creating and combining data sets, and to associate error with alternative decisions. One question raised was

[18] For details regarding individual breakout groups, see <https://www.evergreen.edu/bdei/presentations/tuesbreakout2_combined.pdf>.

[19] See <http://www.cse.ogi.edu/forest/papers/blm-briefing.ppt>; <http://www.evergreen.edu/bdei/presentations/borning.pdf>; and <http://www.evergreen.edu/bdei/presentations/hert_tuesdaylunch1.pdf>, respectively.

whether metadata could become an obligatory part of the data set.

The general problem of data quality in decision making can be summarized as follows: how should uncertainty be determined and communicated to decision makers in studies integrating multiple data sources? The overarching research issue raised by this problem is the extent to which uncertainty associated with data quality and synthesis really has an influence on policy making and plan implementation. This issue comes up in both individual studies and data sharing. For example, in individual studies diverse data sources are combined, and one would like to know the points where error is introduced. Research is needed to develop methods for (1) reducing the introduction of error when data sets are created and combined, (2) measuring and logging error at each stage of the study, and (3) characterizing relationships among errors—additive, multiplicative, averaging.

Where data are shared, for example in data harvesters such as NSF's Long Term Ecological Research (LTER) network's Climate (CLIMDB) and Hydrology (HYDRODB) Database projects, the major issue is the extent to which metadata can become an integral part of the data set. Thus, for example, what happens to metadata when multiple sources are integrated? How can metadata management be automated once it is created? How can data standardization help the process of combining metadata from multiple sources? Can open-source tools be developed for mapping data content standards to one another? The research challenge is to determine how general the tools (that manage data quality in individual and shared studies) can become, and whether they can be applied to a wide range of ecological data sets.

Work has been done by the Federal Geographic Data Committee (FGDC) within the USGS, including a biology standard developed by the NBII Program in the mid-1990s. Metadata standards are well developed and in use by the NSF-sponsored LTER information managers, and these standards are used in internal reviews of NSF LTER projects. It was suggested that NSF develop and publish metadata standards across all grants, instead of just for particular programs such as the LTER.

To determine whether uncertainty associated with data synthesis really has an influence on policy making and plan implementation, studies could be done of decision makers' perceptions of the value of science findings made from synthesized or integrated data. For example, data harvesters such as CLIMDB and HYDRODB have generated publications from combined data sets, which are (perhaps) being used by land managers or decision makers in the Forest Service and the National Oceanic and Atmospheric Administration (NOAA). This work could be extended by examining how syntheses of data sets are used by decision makers and how apparent and how important the errors were to them. Specifically, the research question is, how is the increase in power associated with data synthesis balanced by the increase in uncertainty associated with the ways the errors were combined? An extension of this work could examine how synthetic studies stand up in courts of law compared to other forms of "expert testimony."

Given that the problem of data quality in decision making is how to determine and communicate uncertainty to decision makers, the research question is, does uncertainty associated with data quality and synthesis really influence policy and planning? There are two issues—where diverse data sources are combined and how metadata can become a part of the data set. Participants presented stories corresponding to the research issues. Why couldn't NSF publish metadata standards across all grants, instead of just for certain programs?[20]

[20]For more detail, see <https://www.evergreen.edu/bdei/presentations/wedbo3dataqualityb.pdf>.

Data Integration and Ontologies

Data integration involves mechanisms for reliable, transparent, and authoritative data combination. Associated research issues include defining the dimensions of integration; quantifying semantic distance; integrating multiple ontologies; promoting document modeling; evaluating the utility of qualitative and quantitative data; the need for tools to support data integration; and how one evaluates knowledge from nontraditional sources.

Ontologies are useful for providing metadata over databases, making cross-disciplinary connections, and supplying thesauri. Ontologies on the grid would help users find data and functionality. Tools to build, verify, and deliver ontologies still require considerable research. Other phenomena that require research are understanding gaps and inconsistencies in ontologies, trusting and verifying the content of ontologies, and understanding and handling change in the material represented by ontologies in ways that go beyond simple versioning.

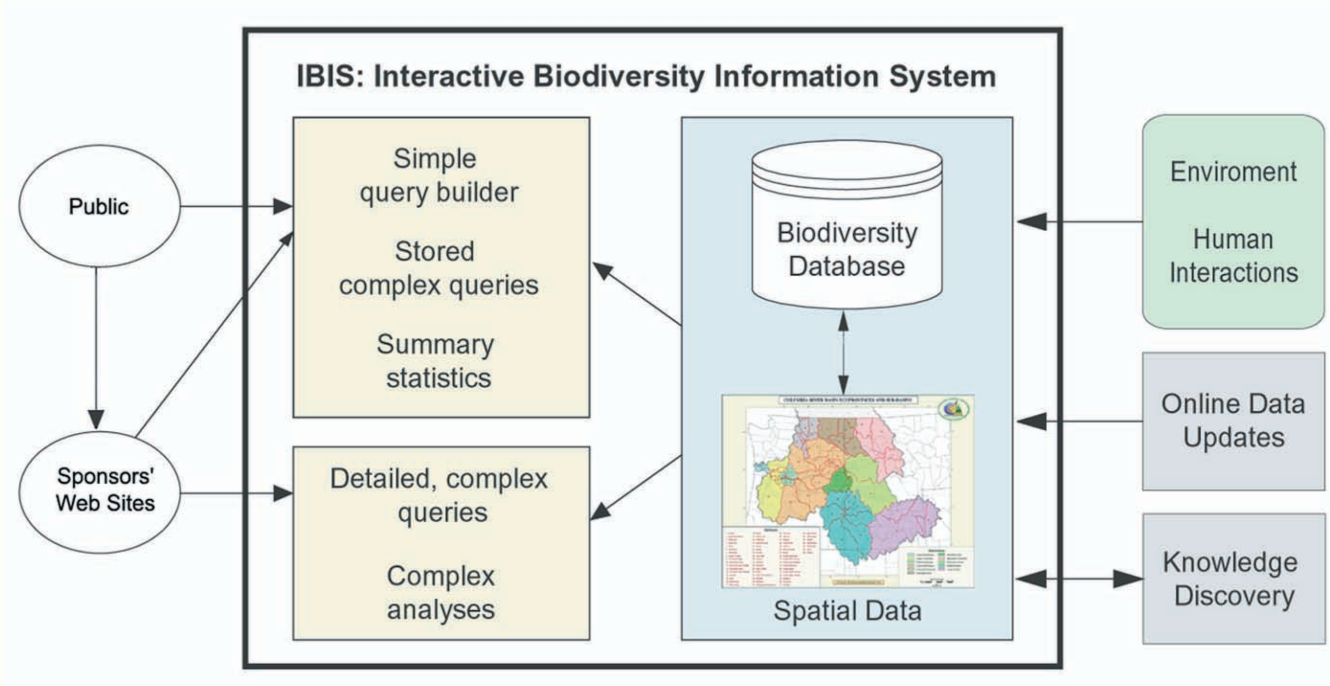
The reclassification of rainbow trout as salmon in the early 1990s and a subsequently implemented information system had broad-reaching effects, the moral being that no indicator is innocent and IT systems have social consequences. Data collection, ontologization, and modeling embody value judgments—how can computer scientists and developers be sensitized? The semantics of BDEI are critical, and include defining and operationalizing meanings, data standardization, and semantic services. Transferring knowledge from other domains to BDEI is itself research. Quality control, data access, and collaborative decision-making support are also critical. Future IT applications should warn scientists and policy makers of impending circumstances.[21]

Social and Human Aspects

Research issues identified in this area included collaboration in eco-informatics tool development and information sharing among decision makers (e.g., measuring success, determining appropriate institutional designs and incentives or disincentives); human-computer interaction (human/tools interface); impact on management practices; education and training (data management domain procedures); and user needs (user requirements, system design).

Advancing the eco-informatics agenda hinges on both new technologies and new understandings of how information infrastructures interrelate between individuals, organizations, communities, disciplines, information resources, and tools. Consider state agency official "Jane Doe" prioritizing parcels for conservation. She is interested in forecasting land use change over a region with the hope that the forecast will identify the habitat parcels most threatened by human encroachment. Ideally, Jane would like some kind of policy-relevant modeling capability to help identify the "development fringe," but she cannot create that on her own. Because others, whom Jane might not even know about, may be well on their way to doing this, tools to facilitate the investigation would include library management systems and newer, innovative collaboration tools and computer-based land use change models. The breakout group considered this scenario as it would play out now versus how it would be different in ten years if the recommended research were successful. A second scenario involving the Death Valley National Park Devils Hole Pupfish illustrated an immediate need for tools that integrate information over time and across agencies, evaluate legacy data, identify indicators, visualize alternative actions, model current ecological conditions, and find similar studies.[22]

[21] See <https://www.evergreen.edu/bdei/presentations/wedbo3ontology.pdf>.
[22] For more detail, see <https://www.evergreen.edu/bdei/presentations/wedbo3HumanCenterednesssummaryc.pdf>.



Interactive Biodiversity Information System: A Triad Approach

The NBII Pacific Northwest Information Node has partnered with the Northwest Habitat Institute to bring their Interactive Biodiversity Information System (IBIS) online. Recently the Institute, working with the Oregon Department of Transportation and Parametrix, Inc., used IBIS to develop a new innovative approach of species, habitats, and functions to produce a Habitat Value when determining project impacts to fish and wildlife. This method was adopted by 11 state and federal agencies and offers a way of addressing ecosystems while making a significant step toward streamlining environmental regulations. To help guide the overall process, Ecoprovince Priorities for species, habitats, and functions are established for each of the 12 regions of the state. Thus, local projects now have a context for their site(s); regional priorities help guide mitigation by establishing banks for habitats other than wetlands, including priority species needs in planning, and incorporating ecological functions into habitat mitigation scenarios. On April 22, 2005, the Oregon Department of Transportation received the Federal Highway Administration's prestigious "Environmental Excellence Award for Environmental Streamlining." The award recognizes their unique approach to the management of highway bridges throughout the state while addressing environmental issues and also saving time and money. See <http://www.nwhi.org/>.

Conclusions and Recommendations

One metaphor that could be used to understand the natural resource management vision that workshop participants would like to convey is a fictitious, ideal decision-making tool.[23] The tool, dubbed Yoda, considers decision makers as those who choose among alternatives, and defines what they do as integrating data via sharable data structures, compatible software tools, human collaboration, and understanding outcomes. Theirs is an awesome task that involves ontologies, semantic distances, and data quality assessment, among other things, and many complex steps.[24]

The sheer number, breadth, and complexity of problems and potential solutions suggested at this workshop dictate that it will take decades to solve them—and all the while species and ecosystems will disappear at an increasing rate. Thus, we need to continually prioritize the critical informatics problems, asking, for example, where these problems intersect across agencies and environments to create the greatest synergies. Which of those with the greatest intellectual merit could be solved with focused research and development? Where could public and private funds be leveraged? These questions could be addressed by follow-on workshops every five years of eco-informatics professionals and computer scientists, each followed by an online survey, auction, or futures market. Because problems are both technical and sociological, a few well-chosen broad projects in those areas could serve other more focused research.

Two critical issues not addressed directly in the workshop but that emerged as participants followed the agenda set by the workshop steering committee are feedback loops and the nature of decision making. One senior scientist insisted that if a resource manager becomes more effective at what he or she does, the effect of that manager on the system he or she manages is not negligible. We know very little about this problem.

Understanding the nature of decision making is as critical to those conducting research in this area as the feedback problem is. Because knowledge of decision making for natural resource management came to be viewed during the workshop as so critical to future eco-informatics research, workshop participants formed a task force to report back on the nature of decision making as "approaches to help actors make decisions among alternatives." The team noted that the domain is particularly difficult because it includes both public policy and the complexity of eco-systems. One significant difference between a research approach and decision-making requirements is that environmental issues are complex and involve considerable uncertainties, but in political and policy situations, many decisions are placed in a "yes or no" context. Thus, in addition to understanding one's own major research themes, anyone conducting research in this area must also have an understanding of decision making in general, as well as in the context of eco-informatics. Fülöp and Schweik, together with their colleague David Roth, contributed a primer on decision science for computer scientists and social scientists interested in eco-informatics, which is included in this report as Appendix 1.

Communication enables the collaboration, trustworthiness, and data sharing that in turn enable better decision making. Improved human-computer interaction in software (human-centered applications), and significant use of ontologies and modern data integration strategies are required to enable that communication. Ontologies, coupling diverse models, and

[23]This point was raised by Nancy Tosta in her presentation at the workshop.
[24]See <https://www.evergreen.edu/bdei/presentations/GreybeardNT.pdf>.

learning how second- and third-generation metadata can be used to define data quality are particularly important. One real challenge of this area is the difficulty involved in pursuing research in one of these areas without at least some understanding of the others. Social science is characterized by indigenous local and community knowledge, plus the ethics of decision making and user needs. Without a social science perspective on technology, it seems unlikely that the right research will be done, or that the research can be appropriately applied.

Another challenge involves training computer scientists and social scientists to work in eco-informatics and natural resource management. A team of graduate students at The Evergreen State College participated in the workshop as observers and reported on how researchers might articulate the educational impacts of their work. Involving students in research and using their research as a teaching tool requires transdisciplinary communication, new methods for collaboration, language that integrates concepts across disciplines, information dissemination, and eco-informatics educational materials. The students saw the ethical issues around large data repositories as a particularly fruitful area for teachable moments. Funding interdisciplinary mission-oriented tasks that address local problems was seen as a way to work toward these goals. The students encouraged NSF to partner with agencies that support applied student research.[25]

Workshop participants wanted the early focus in eco-informatics and decision making to be on ecological and biodiversity issues, as it was strongly believed that environmental health decision making is even more complex and requires natural resource management as input.

Funding agencies must work together and with principal investigators, information managers, and decision makers to sustain and encourage innovation, research, and development in this area. How will researchers funded by NSF find resource managers with whom to collaborate in the field so they can best understand resource problems in adequate detail, extract the research issues, and test prototypes? How will research results and prototypes funded by NSF make their way to resource managers in the form of information technology deployed in field offices? How will the evaluation of new products, and an understanding of their strengths and weaknesses, be fed back into this loop to inform new research? In addition to being requirements of the research agenda of eco-informatics for decision making, these questions are themselves research areas.

Considerable attention must be paid to assuring a cycle of innovation from research to prototype, to development and commercialization, and finally to deployment and evaluation (and back to research). The differing, nonoverlapping missions and reward systems built into each agency make it too easy to lose momentum at any of these stages. Longer funding cycles, punctuated by regular review and continuing applied research proposal submission, are needed to elicit requirements and integrate them into a research agenda, and to enter into an "agile" software cycle of development, evaluation, and deployment. One year is barely adequate for the first step (eliciting requirements, understanding the domain, and setting up a collaboration); three to five years are needed to develop and evaluate tools with decision-maker collaborators. Special two-year supplements for deployment (given prior evaluation) are often required to initiate an innovation cycle.

[25]See <https://www.evergreen.edu/bdei/presentations/gradStudentDraft.pdf>.

Further, considerable attention must be paid to constantly reprioritizing the research agenda and assuring the development of tools that promise, through extensibility, applicability to a wide range of problems as they arise in important ecosystems. Workshop participants emphasized the importance of keeping a range of research projects in the pipeline—from those that are highly theoretical and generalizable; to working prototypes developed by researchers and resource managers; to deployment experiments, sanctioned, vetted, and supported by organizations with responsibilities for resource management. Finally, workshop participants felt that a cross-agency funding initiative should be pursued to support the major research challenges outlined in this report.

Acknowledgments

The authors thank those who presented research, development, and needs assessments at the workshop, all of which informed this report, as well as the workshop participants who contributed to this report in intensive working sessions at the workshop. Special thanks go to János Fülöp of the Hungarian Academy of Sciences, and to David Roth and Charles Schweik, both of the University of Massachusetts-Amherst, for writing "Decision Making in the Context of Eco-Informatics," which appears as Appendix 1 to this report.

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Case Studies:
- Illustration, page 11 (top), provided by Steve Williams; text provided by Kevin Gergely
- Illustration and text, page 11 (bottom), provided by Sherry Pittam
- Illustration, page 12, provided by Fred Rascoe; text provided by Jean Freeney
- Illustration and text, page 17, provided by Tom O'Neil

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Appendices

Appendix 1.

Decision Making in the Context of Eco-informatics

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Introduction

The central goal of the BDEI-3 workshop report is to define a research agenda for eco-informatics and decision making. To do this, it is important to first define what "decision making" means in the context of eco-informatics.

A starting point is the definition provided by Harris (1998): "Decision making is the study of identifying and choosing alternatives based on the values and preferences of the decision maker." In the context of eco-informatics, the decision maker might be a policy maker (e.g., a politician) or one of his or her analysts, a public agency official managing or working within some environmental program (e.g., a public employee in the U.S. EPA, the USDA Forest Service, or a state or local agency), a manager or staffperson in a nonprofit organization such as the Nature Conservancy, a citizen environmental advocacy group, employees in a private firm involved in some environment-related decision, or even "citizen-scientists" interested in a particular environmental problem or issue. Decision-making processes in the context of eco-informatics (and this report) involve any of these actors or combinations of actors, such as in the context of a town meeting or a public comment period.

Decision-making Processes in the Public Management Literature

Over the years, there has been much debate about how to accurately describe decision-making processes in general. Beyond an implicit agreement that decisions are made through some sort of process, chaotic or otherwise, there is little else that scholars agree on. Given that much of the decision making in eco-informatics involves public sector agencies, this review will focus primarily on decision making in this sector.

Rainey (2003, 160–69) summarizes variations on four major approaches to decision making found in public management literature, none of which is uncontested:

1. **The "Rational Decision-Making" approach.** This view of decision making suggests that decision makers follow a specific process through which goals are decided, alternatives are developed in accordance with those goals, and "the most efficient" alternative is implemented (Baker et al. 2001; Rainey

2003; Kingdon 2003). Stone (2002, 377) refers to this approach as following a "conveyor belt" process. Rainey (2003, 161) provides a hypothetical example where an organization needs copying machines. A report on three vendors supplying identical machines is developed. The report is reviewed by a manager and the least expensive one is chosen. As Rainey states, to choose another vendor "would invite others to question the [manager's] competence, ethics, or sanity."

2. **The "Contingency Perspectives Decision-Making" approach.** Some scholars assert that rational decision making can only occur under "stable, clear, simple conditions" (Rainey 2003, 164). Because these conditions are often not present, decision makers must use judgment and intuition, bargaining and maneuvering politically in their decision-making process. According to Rainey, James Thompson asserted that the level of agreement among decision makers on goals and the amount of technical knowledge decision makers have about how to implement solutions or tasks determine whether a decision-making process can be rational. When the level of agreement and the amount of knowledge are high, rational processes are more likely to be followed (2003, 164).

3. **The "Incremental Decision-Making" approach.** Relying on Charles Lindblom's "The Science of Muddling Through" (1950), Rainey states that the responsiveness of decision makers to "the requirement for political consensus and compromise" necessarily leads to unclear goals that result in restricting "the size of the changes [decision makers] propose" (Rainey 2003, 165–66). In other words, instead of choosing an alternative that a rational decision-making process would predict, decision makers choose to make less controversial, intermediary decisions to ensure some degree of success in achieving the vague goals presented.

4. **"The Garbage Can Decision-Making" approach.** This idea "comes from the observation that decisions are made in organizations when particular decision-making opportunities or requirements arise" (Rainey 2003, 167–68). In this model, "it is often unclear who has the authority to decide what and for whom" (Rainey 2003, 168). It is the antithesis of the rational decision-making model; solutions can be developed before problems are determined to exist (*id.*; see also Kingdon 2003, 84–86). In other words, instead of following the aforementioned "conveyor belt," decision makers may be waiting for an opportunity to advocate actions already planned. Once attention is brought to a problem related to their kept-on-the-shelf action, decision makers then propose it. (Kingdon's term for this opportunity is a "policy window" [2003, 166].)

In the domain of environmental management or policy, it is probably safe to say that most developers of eco-informatics tools or information *hope* that their work will be used in some form of rational decision-making processes, or at the very least, that their tools and information will be used to help inform incremental decision-making processes. For example, Tonn et al. (2000, 165–66) provide a framework to guide environmental decision making in which goals and values are agreed on, planning is pursued, and decisions are developed and implemented. Elements that compose an environmental decision include the goals and values of the parties involved, the conflicting perceptions of the problem, and the available knowledge (e.g., eco-informatics-based information). Within this broad context, issues are diagnosed, hopefully with a combination of general foresight, a monitoring of the environmental status quo, and an evaluation of decisions already made. As issues are diagnosed, appropriate "decision-making modes" are assigned. These modes include, among others, "emergency action," "routine procedures," and "collaborative learning," each representing a different decision-making attitude within the framework (Tonn et al. 2000, 170–71). Once the mode is assigned, the decision is developed through a series of rational steps: issue familiarization, criteria setting, option construction, option assessment, and arrival at a decision. Eco-informatics come into play in various parts of this framework, including issue diagnosis, monitoring the present situation, and option construction (see Tonn et al. 2000, 169, 168, and 174). Although "eco-informatics" is not a term used by Tonn and colleagues, the general supporting data and models they refer to would be considered eco-informatics components.

Approaches to Help Actors Decide Between Alternatives

There is a vast body of literature in fields such as operations research, decision or management science, ecological economics and others that describes various approaches to help single or group decision makers analyze their situation and weigh alternative choices. Many of these approaches are designed to be used in rational decision-making settings (described earlier), but they might also be applied in some "incremental" eco-informatics decision-making settings.

Optimization approaches (e.g., linear or nonlinear programming, discrete optimization) can be applied in decision settings where there is a single criterion to base a decision on (such as cost) (Nemhauser et al. 1989). Multiple criteria optimization techniques also exist when there are a finite number of criteria, but the number of alternatives to choose from is infinite (Steuer 1986). Perhaps more common are decision situations where there are a number of criteria and alternatives to consider. These types of decision-making situations, where the goal is to identify a single most preferred alternative, are referred to as multi-attribute decision-making problems. Simple approaches not requiring computing have been developed, such as "pros and cons analysis," minimax and maximax methods, conjunctive and disjunctive methods, and lexicographic methods (Baker et al. 2001; UK DTRL 2001), but these are best suited for problems with a single decision maker and few alternatives. These approaches tend not to be characteristic of environmental decision-making settings (Linkov et al. 2004).

At the same time, more sophisticated and computer-based methods for decision analysis have emerged, including approaches based on Multi-Attribute Utility Theory (MAUT), outranking, and cost-benefit analysis.[1] These, along with many other computer-based analytic tools and approaches (such as GIS-based models or quantitative analysis based on empirical data) provide examples of the intersection of eco-informatics and decision making, perhaps more often in the context of one analyst or one organization.

Other settings, however, involve groups of people or organizations trying to make a decision related to the environment or environmental management and policy, and in these settings, there are relevant multi-attribute decision-making approaches. For example, Bose et al. (1997) provide a review of early MAUT methods applied to group settings. One such approach, the Analytic Hierarchy Process (Saaty 1980) has been applied to group settings (see Dyer and Forman 1992; Lai et al. 2002; and an alternative approach proposed by Csáki et al.1995). These types of situations—where the preferences of various groups or stakeholders need to be considered—are a critical research area in the eco-informatics and decision-making domain.

Another important point related to the various decision-making tools and approaches cited above, as well as others

[1]For MAUT, see Keeney and Raiffa 1976; Edwards 1977; Edwards and Barron 1994; Mészáros and Rapcsák 1996; Saaty 1980; Triantaphyllou 2000; and Figueira et al. 2004. For outranking, see Roy 1968; Brans and Vincke 1985; Brans et al. 1986; UK DTLR 2001; and Figueira et al. 2004. For cost-benefit analysis, see UK DTLR 2001.

falling in the domain of eco-informatics, is that often variables used in computer-based models (such as multi-attribute decision models) are set to subjective values. These models may contain uncertainties, either because of subjective scoring or because they are based on some data or model output that contains a level of uncertainty. It is therefore important to ask how the final ranking of alternatives is sensitive to the changes of input parameters contained within the decision model and how uncertainties are communicated to the user through analytic tools. Examples of research in this area include Triantaphyllou and Sanchez (1997), Mészáros and Rapcsák (1996), and Ekárt and Németh (2005).

Two Important Issues: Politics and Complexity

Until now, the discussion has focused primarily on decision-making situations that are more rational or perhaps incremental in nature. However, some scholars lament that eco-informatics-based tools, computer-based models, and data are utilized as "weapons in political and policy warfare," while other scholars accept this supporting role, focusing more on how they are used to persuade decision makers to accept alternative interpretations of the information (King and Kraemer 1993; Mazurek 1996; Hendriks et al., 2000). Back in 1993, King and Kraemer noted that computer-based models were specifically constructed to provide results that supported proposed policies of decision makers. It is likely that in the 15 or more years since this use (or misuse?) of eco-informatics tools and information, use has only increased as eco-informatics tools have become easier for policy analysts to use.

Others worry about the complexity of eco-informatics-based computer models and the ability of decision makers to understand them. One problem is that in environmental situations, issues are complex and there may be uncertainties, but in political and policy situations, many decisions are placed in a "yes or no" context. Another issue has to do with the complexities of eco-informatics tools and output and the frequent need to communicate results to policy makers and analysts (and citizens) who may not have the educational background to understand them. For example, Briassoulis (2000) states that, though models (in her case, computer-based land-use models) should be developed with a wide variety of users in mind (e.g., education level), models are instead being developed solely for an "elite of educated users." Given that decision makers may not fall into this elite group, Briassoulis argues that it is the elite's responsibility to educate, objectively, decision makers on the assumptions and conditions relied on in such decision-support models (*Id.*). Still, she is optimistic that such models, if developed properly, can positively support decisions in the process of being made.

In many (perhaps most) contexts, it is probably the case that developers of eco-informatics tools create these methods without too much concern for the context in which such tools will be applied to decision making. Developers may focus more on getting the tool right (scientifically) and concentrate less on how the tool might be used or abused in particular decision-making settings. A simple example of this is in the evolution of statistical software, where it becomes easier and easier for a user to run a method with little or no understanding of the assumptions or processing being done "under the hood."

Conclusion

To summarize, literature on public-sector decision making emphasizes that it is not a benign pursuit.[2] There is no real consensus on how decisions are made. Theories range from mechanical approaches (Rational Decision Making) to those that assume no constants at all (Garbage Can). Within environmental decision making, the quest for a more efficient means of developing policy is still ongoing. The role of support-

[2]We should note that in preparing this paper, we also did research on decision-making processes in nonprofit organizations, knowing that they, too, are extremely active in eco-informatics-based decision making. Much of what we described earlier is probably also relevant to both private and nonprofit settings, and Rainey (2003) makes this point.

ing, scientific information (e.g., eco-informatics-based information) in environmental decision making is also being debated. This is one reason why this particular workshop on eco-informatics and decision making is important.

The "ideal" model of eco-informatics decision making follows a rational process in which decisions are informed by "facts" generated through good science coupled with eco-informatics tools, procedures, and analyses. The reality is that decision making (at least in the public sector, but probably in other sectors as well) often involves processes that do not follow a "rational" approach, as well as uncertainty in the data or analyses and pressure from competing political interests. Given the complexities inherent in public sector decision-making processes, none of these statements should be surprising. However, a research program centering on eco-informatics and decision making should be cognizant of these environments and perhaps help to alleviate—or at least expose—some of the negative consequences of these kinds of "nonrational" processes.

References

Baker, D., D. Bridges, R. Hunter, G. Johnson, J. Krupa, J. Murphy, and K. Sorenson. 2001. *Guidebook to decision-making methods.* WSRC-IM-2002-00002, U.S. Department of Energy.

Bose, U., A. M. Davey, and D. L. Olson. 1997. Multi-attribute utility methods in group decision making: Past applications and potential for inclusion in GDSS. *Omega* 25:691–706.

Brans, J. P., and Ph. Vincke. 1985. A preference ranking organization method. *Management Science* 3:647–56.

Brans, J. P., Ph. Vincke, and B. Marechal. 1986. How to select and how to rank projects: The PROMETHEE-method. *European Journal of Operational Research* 24:228–38.

Briassoulis, H. 2000. Analysis of land use change: Theoretical and modeling approaches. The Web Book of Regional Science. <http://www.rri.wvu.edu/WebBook/Briassoulis/contents.htm>.

Csáki, P., T. Rapcsák, P. Turchányi, and M. Vermes. 1995. Research and development for group decision aid in Hungary by WINGDSS, a Microsoft Windows–based group decision support system. *Decision Support Systems* 14:205–21.

Dyer, R. F., and E. H. Forman. 1992. *Group decision support with the Analytic Hierarchy Process. Decision Support Systems* 8:99–124.

Edwards, W. 1977. How to use multiattribute utility measurement for social decision making. *IEEE Transactions on Systems, Man, and Cybernetics.* SMC-7:326–40.

Edwards, W., and F. H. Barron. 1994. SMARTS and SMARTER: Improved simple methods for multiattribute utility measurements. *Organizational Behavior and Human Decision Processes* 60:306–25.

Ekárt, A., and S. Z. Németh. 2005. Stability analysis of tree-structured decision functions. *European Journal of Operational Research* 160:676–95.

Figueira, J., S. Greco, and M. Ehrgott, eds. 2004. *Multiple criteria decision analysis: State of the art surveys*. New York: Springer.

Harris, R. 1998. *Introduction to decision making.* <http://www.virtualsalt.com/crebook5.htm>. Accessed 1/4/2005.

Hendriks, C., et al. 2000. Material flow analysis: A tool to support environmental policy decision making. Case studies on the city of Vienna and the Swiss lowlands. *Local Environment* 5(3):311–28.

Fülöp, J., 2005. Introduction to decision-making methods. Paper developed for the BDEI-3 Workshop, The Evergreen State College, December 13–15, 2004, Olympia, Washington.

Keeney, R. L. and H. Raiffa. 1976. *Decisions with multiple objectives: Performances and value trade-offs.* New York: Wiley.

King, J., and K. Kraemer. 1993. Models, facts, and the policy process: The political ecology of estimated truth. In *Environmental Modeling with GIS,* ed. M. F. Goodchild, B. O. Parks, and L. T. Steyaert, 353–60. New York: Oxford University Press.

Kingdon, J. 2003. *Agendas, alternatives, and public policies.* New York: Longman.

Lai, V. S., K. W. Bo, and W. Cheung. 2002. Group decision making in a multiple criteria environment: A case using the AHP in software selection. *European Journal of Operational Research* 137:134–44.

Lindblom, C. 1950. The science of muddling through. *Public Administration Review* 19 (1):79–88.

Linkov, I., A. Varghese, S. Jamil, T. P. Seager, G. Kiker, and T. Bridges. 2004. Multi-criteria decision analysis: A framework for structuring remedial decisions at the contaminated sites. In *Comparative risk assessment and environmental decision making,* ed. I. Linkov and A. B. Ramadan, 15–54. New York: Springer.

Mazurek, J. 1996. The role of health risk assessment and cost-benefit analysis in environmental decision making in selected countries: An initial survey. Discussion Paper 96-36. Resources for the Future, Washington, D.C. Available through <http://www.rff.org>.

Mészáros, Cs. and T. Rapcsák. 1996. On sensitivity analysis for a class of decision systems. *Decision Support Systems* 16:231–40.

Nemhauser, G. L., A. H. G. Rinnoy Kan, and M. J. Todd. 1989. *Optimization.* Vol. 1 of *Handbooks in operations research and management science.* North-Holland: Amsterdam.

Rainey, H. 2003. *Understanding and managing public organizations.* San Francisco: Jossey-Bass.

Roy, B. 1968. Classement et choix en présence de points de vue multiple (la méthode electre). *RAIRO* 2:57–75.

Saaty, T. L. 1980. *The analytic hierarchy process.* New York: McGraw-Hill.

Steuer, R. E. 1986. *Multiple criteria optimization: Theory, computation, and application.* New York: Wiley.

Stone, D. 2002. *Policy paradox and political reason.* New York: W. W. Norton & Co.

Tonn, B., M. English, and C. Travis. 2000. A framework for understanding and improving environmental decision making. *Journal of Environmental Planning and Management* 43(2):163–83.

Triantaphyllou, E. 2000. *Multi-criteria decision-making methods: A comparative study*. Dordrecht: Kluwer Academic Publishers.

Triantaphyllou, E., and A. Sanchez. 1997. A sensitivity analysis approach for some deterministic multi-criteria decision making methods. *Decision Sciences* 28:151–94.

UK DTLR. 2001. *Multi-criteria analysis: A manual.* Department for Transport, Local Government and the Regions, UK. <http://www.odpm.gov.uk/stellent/groups/odpm_about/documents/page/odpm_about_608524.hcsp>.

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Appendix 3. Acronyms Used

BDEI	Biodiversity and Ecosystem Informatics
BoF	Birds of a Feather
CS/IT	Computer Science/Information Technology
ECOS	Environmental Council of the States
EI	Eco-informatics
EPA	Environmental Protection Agency
FGDC	Federal Geographic Data Committee
FWS	U.S. Fish and Wildlife Service
GAP	Gap Analysis Program
GEDE	GAP Ecosystem Data Explorer
GIS	Geographic Information System
HCI	Human-Computer Interaction
IBIS	Interactive Biodiversity Information System
IT	Information Technology
LTER	Long Term Ecological Research
NASA	National Aeronautics and Space Administration
NBII	National Biological Information Infrastructure
NGO	Nongovernmental Organization
NSF	National Science Foundation
NOAA	National Oceanic and Atmospheric Administration
PCAST	President's Committee of Advisors on Science and Technology
SRFS	Snake River Field Station
USGS	U.S. Geological Survey

Appendix 4. Selected Web Sites

dg.o 2005. Panel, Digital Government and the Academy (Delcambre, Giuliano), May 16–18, 2005. <http://dgrc.org/dgo2005>

dg.o 2004. Birds of a Feather (Schweis et al.), May 24–26, 2004. <http://dgrc.org/dgo2004/disc/bofs/bof_ecoinformatics.pdf>

PCAST. Panel on Biodiversity and Ecosystems, "Teaming with Life: Investing in Science to Understand and Use America's Living Capital," March 1998. <http://www.nbii.gov/about/pubs/twl.pdf>

BDEI - Biodiversity and Ecosystem Informatics Workshops

BDEI-1. NSF, USGS, NASA Workshop (Maier, Landis, Cushing, Frondorf, Silberschatz, Frame, Schnase), NASA (Goddard), June 2000. <https://www.evergreen.edu/bdei/2001/>

BDEI-2. Principal Investigators' Meeting Report (Cushing, Beard-Tisdale, Bergen, Clark, Eckman, Henebry, Landis, Maier, Schnase, Stevenson), NSF (Arlington), February 10, 2003. <https://www.evergreen.edu/bdei/2003/>

BDEI-3. Eco-Informatics for Decision Makers: Advancing a Research Agenda (Cushing, Wilson, et al.), The Evergreen State College, December 13–15, 2004. <http://www.evergreen.edu/bdei/>